

MOLECULAR ENVIRONMENT AND AN X-RAY SPECTROSCOPY OF SUPERNOVA REMNANT KESTEVEN 78

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ABSTRACT

We investigate the molecular environment of the Galactic supernova remnant (SNR) Kesteven 78 and perform an *XMM-Newton* X-ray spectroscopic study for the northeastern edge of the remnant. SNR Kes 78 is found to interact with the molecular clouds (MCs) at a systemic local standard of rest velocity of 81 km s^{-1} . At around this velocity, the SNR appears to contact a long molecular strip in the northeast and a large cloud in the east as revealed in the ^{13}CO line, which may be responsible for the radio brightness peak and the OH maser, respectively. The ^{12}CO -line bright region morphologically matches the eastern bright radio shell in general, and the SNR is consistent in extent with a CO cavity. Broadened ^{12}CO line profiles discerned in the eastern maser region and the western clumpy molecular arc and the elevated $^{12}\text{CO } J=2-1/J=1-0$ ratios along the SNR boundary may be signatures of shock perturbation in the molecular gas. The SNR-MC association places the SNR at a kinematic distance of 4.8 kpc. The X-rays arising from the northeastern radio shell are emitted by underionized hot ($\sim 1.5 \text{ keV}$), low-density ($\sim 0.1 \text{ cm}^{-3}$) plasma with solar abundance, and the plasma may be of intercloud origin. The age of the remnant is inferred to be about 6 kyr. The size of the molecular cavity in Kes 78 implies an initial mass around $22M_{\odot}$ for the progenitor.

Subject headings: ISM: individual objects (G32.8–0.1 = Kes 78), — ISM: molecules, — supernova remnants

1. INTRODUCTION

Born in giant molecular clouds (MCs), massive stars evolve from collapsing molecular cores to core-collapse supernovae. During their short lifetimes, they evacuate a cavity with their energetic winds and ionizing radiation, and later the supernova shocks will often collide with the cavity wall. In the past three decades, dozens of supernova remnants (SNRs) were found to be in physical contact with MCs (see Jiang et al. 2010 and references therein). In particular, the 1720 MHz OH masers, collisionally excited by the shock-heated molecular gas, have been regarded as the signposts of SNR-MC interaction (e.g., Frail et al. 1996; Lockett et al. 1999; Frail & Mitchell 1998; Wardle & Yusef-Zadeh 2002). Recently, several GeV and TeV sources were found to spatially correspond to MCs that are associated with SNRs, such as IC443 and W28, in which $p-p$ collision plays an important role in the gamma-ray emission. Detailed investigation of the molecular environment of the interacting SNRs is therefore of great interests.

Kesteven 78 (G32.8–0.1), with a partly brightened radio shell, was identified as a Galactic SNR by Caswell et al. (1975) based on the 408 and 5000 MHz observations. A distance of $\sim 8 \text{ pc}$ was estimated using the radio surface brightness – diameter ($\Sigma-D$) relationship (Caswell et al. 1983). A 21cm HI observation with a resolution $2' \times 130' \times 6.3 \text{ km s}^{-1}$ was made by Gosachinskii & Khersonskii (1985), which suggested a corresponding local standard of rest (LSR) velocity of 90 km s^{-1} , a distance of 9 kpc, and an age of 12 kyr for the SNR. Kas-

sim (1992) derived the spectral index as -0.5 . A single 1720 MHz hydroxyl (OH) maser spot at LSR velocity 86.1 km s^{-1} was detected on the radio shell by Koralesky et al. (1998) in the Very Large Array (VLA) observations, which indicates a shock interaction with MCs; a distance of 5.5 or 8.8 kpc was then suggested on the assumption that the shock propagation is perpendicular to line of sight (LOS). A classical antisystematic S-shaped profile of Stokes V was also detected, suggesting the presence of Zeeman splitting. A millimeter-wavelength $^{12}\text{CO } (J=1-0)$ observation was carried out by Zhou et al. (2007), which suggests that an eastern molecular gas detected in the velocity range $72-88 \text{ km s}^{-1}$ is related to the SNR, and no line broadening was found from it. In a *Spitzer*-IRAC mid-infrared (IR) survey of Galactic SNRs, which was made to search for IR counterparts with existing radio images, Kes 78 is classified as “not detected but confused” one (Reach et al. 2006). In the optical band, filamentary and diffuse emission is detected in the SNR; the $[\text{SII}]/\text{H}\alpha$ ratio higher than 1.2 is extensively found, suggesting that the optical emission arises from the shock-heated gas (Boumis et al. 2009, B09). An extended very high energy (VHE) γ -ray source HESS J1852–000 is revealed by the H.E.S.S. team to be close to the east edge of the remnant.⁴

Motivated by the indication of the OH maser for SNR–MC interaction; a hint of the previous CO observation for a related MC in the east; and the irregular morphology of the SNR, which implies a complex, non-uniform ambient medium, we examine the detailed distribution of the environmental molecular gas and its physical relation with Kes 78, based on both our new and the archival observations of three CO rotational transitions and the

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⁴<http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2011/02/>

archival data of the *XMM-Newton* X-ray observation. In Section 2, we briefly describe the observations and data reduction. Our results are presented in Section 3. Physical properties of the SNR are discussed in Section 4. The conclusions are summarized in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. CO Observations and Data

The observations of millimeter molecular emissions toward SNR Kes 78 were first made in 2009 November with the 13.7 m millimeter-wavelength telescope of the Purple Mountain Observatory at Delingha (hereafter PMOD), China. A superconductor-insulator-superconductor (SIS) receiver and two acousto-optical spectrometers (AOSs) were used to simultaneously observe the ^{12}CO ($J=1-0$) line (at 115.271 GHz) and the ^{13}CO ($J=1-0$) line (at 110.201 GHz). We mapped the radio bright shell region of Kes 78 with $1'$ grid spacing and a $39' \times 27'$ large region centered at ($18^{\text{h}}51^{\text{m}}03^{\text{s}}.97$, $-00^{\circ}12'22''.5$, J2000.0) with $2'$ grid spacing. The AOS bandwidth and velocity resolution are 145 MHz and 0.37 km s^{-1} for ^{12}CO ($J=1-0$) and 43 MHz and 0.11 km s^{-1} for ^{13}CO ($J=1-0$). During the observation epoch, the half-power beam width (HPBW) of the antenna was $56''$, the main beam efficiency was about 62% at zenith, and the pointing accuracy was better than $5''$. The typical system temperature was around 230 K. The observed LSR velocity ranges were -102 to 276 km s^{-1} for ^{12}CO ($J=1-0$) and 28 to 143 km s^{-1} for ^{13}CO ($J=1-0$).

The follow-up observation was made in the ^{12}CO ($J=2-1$) line (at 230.538 GHz) during 2010 January and February using the Kölner Observatory for Submillimeter Astronomy (KOSMA) 3m submillimeter telescope in Switzerland. An SIS receiver and a medium-resolution AOS spectrometer were used. A $31' \times 31'$ area centered at ($18^{\text{h}}51^{\text{m}}03^{\text{s}}.97$, $-00^{\circ}08'22''.5$, J2000.0) was mapped with a grid spacing of $1'$ in on-the-fly mode. The HPBW of the telescope was $130''$, the main beam efficiency was 54% during our observation, and the pointing accuracy was about $10''$. The AOS bandwidth and velocity resolution were about 300 MHz and 0.2 km s^{-1} .

All the CO data were reduced with GILDAS/CLASS package⁵ and analyzed with IDL and KARMA (Gooch, 1996). After the baseline subtraction and the calibration for main beam efficiency and elevation, the spectra were resampled to a uniform velocity resolution of 0.5 km s^{-1} and the data were convolved to a uniform beam size of $2'$. Then the mean rms noise levels of the main beam brightness temperature were 0.18, 0.20, and 0.30 K for the ^{12}CO ($J=1-0$), ^{13}CO ($J=1-0$), and ^{12}CO ($J=2-1$) lines, respectively.

^{13}CO ($J=1-0$) emission data from the Boston University–Five College Radio Astronomy Galactic Ring Survey (BU-FCRAO GRS; Jackson et al. 2006) were also used. They offer a $46''$ angular resolution on a $22''$ grid and a 0.21 km s^{-1} velocity resolution.

2.2. Data of X-Ray and Other Wavebands

The *ROSAT* X-ray image of the SNR Kes 78 region was gained from the *ROSAT* All Sky Survey broadband

data. The *XMM-Newton* data of partial region of Kes 78 were obtained from an observation toward the Galactic ridge centered at ($18^{\text{h}}51^{\text{m}}44^{\text{s}}.67$, $00^{\circ}08'58''.5$, J2000), which was carried out on 2003 November 21–22 (ObsID: 0017740501, PI: F. Azita Valinia) in the full frame mode and with the medium filter. The EPIC data were reprocessed with the Science Analysis System software (SAS, version 9.0.0). After removing time intervals with heavy proton flarings, net exposures of 29 ks and 27 ks remained for EPIC-MOS and EPIC-PN, respectively, and were used for analysis. The *XMM-Newton* field of view (FOV) covers only the northeastern boundary region of Kes 78, which is the brightest region in the 1.4 GHz radio continuum emission.

The *Spitzer* $24 \mu\text{m}$ mid-IR observation used here was carried out as 24 Micron Survey of the Inner Galactic Disk Program (PID: 20597; PI: S. Carey) with the Multiband Imaging Photometer. The $24 \mu\text{m}$ Post Basic Calibrated Data were obtained directly from the *Spitzer* archive. The 1.4 GHz radio continuum emission and the HI-line data were obtained from the archival VLA Galactic Plane Survey (VGPS; Stil et al. 2006).

3. RESULTS

3.1. Molecular Environment

3.1.1. The OH Maser Point and MCs at $V_{\text{LSR}} \sim 81 \text{ km s}^{-1}$

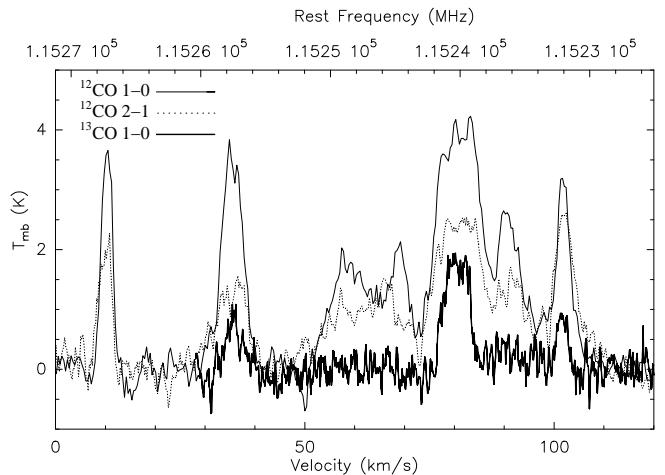


FIG. 1.— ^{12}CO ($J=1-0$) (solid line), ^{12}CO ($J=2-1$) (dotted line), and ^{13}CO ($J=1-0$) (thick solid line) spectra at the maser point. The upper x-axis refers to the rest frequency of the ^{12}CO ($J=1-0$) line. All the spectra are not convolved to a uniform beam size.

We first focus on the molecular gas indicated by the 86 km s^{-1} 1720 MHz OH maser located at ($18^{\text{h}}51^{\text{m}}48^{\text{s}}.04$, $-00^{\circ}10'35''$). The CO spectra at the maser point are given in Figure 1. There are four prominent peaks at $V_{\text{LSR}} \sim 10, 37, 81$, and 102 km s^{-1} . The LSR velocity of the maser, 86 km s^{-1} , is in the red (right) wings of the 81 km s^{-1} ^{12}CO lines, in which ^{13}CO emission is insignificant. A few secondary ^{12}CO components ranging from 52 km s^{-1} to 96 km s^{-1} , with few ^{13}CO

⁵<http://www.iram.fr/IRAMFR/GILDAS>

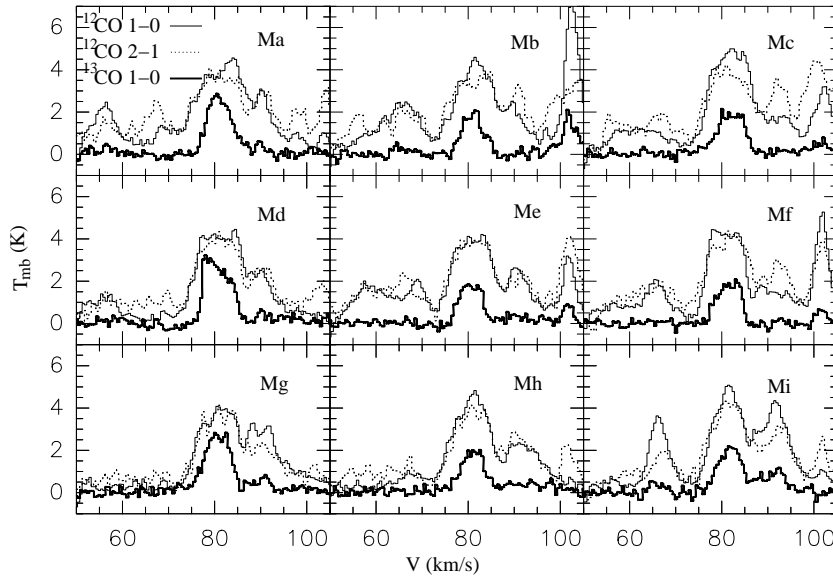


FIG. 2.— Grid of CO spectra restricted to the velocity range 50 km s^{-1} to 105 km s^{-1} in the 1720 MHz OH maser region with $1'$ spacing (labeled as the box “M” in the bottom right panel of Figure 3). Note that the ^{12}CO ($J=2-1$) lines have been multiplied by a factor of 1.6 so as to scale the $\sim 81 \text{ km s}^{-1}$ ^{12}CO ($J=2-1$) peak of the maser point (“Me”) with the ^{12}CO ($J=1-0$) peak. All the spectra are not convolved to a uniform beam size.

counterparts, seem to be linked with the prominent component peaked at 81 km s^{-1} . As ^{13}CO emission, usually optically thin, arises in the quiescent dense gas along the whole LOS, the lack of significant ^{13}CO features at the corresponding LSR velocities indicates that these ^{12}CO secondaries are likely to represent the disturbed gas deviating from the systemic velocity $\sim 81 \text{ km s}^{-1}$, as complicated broadened wings. Similar CO line profiles are also present at points close to the OH maser (point “Me”), as seen in the grid (Figure 2). By scaling the $\sim 81 \text{ km s}^{-1}$ ^{12}CO ($J=2-1$) peaks to match the ^{12}CO ($J=1-0$) peaks, with the maser (“Me”) as the fiducial point, relative enhancement of the ^{12}CO ($J=2-1$) is seen at some points (e.g., “Mb”, “Mc”, and “Mf” at $\sim 90 \text{ km s}^{-1}$ and “Ma”, “Mc”, and “Me” at $\sim 67 \text{ km s}^{-1}$), which may be indicative of relatively warm shocked gas. The shock interaction is also favored by the elevated ^{12}CO $J=2-1/J=1-0$ ratio at $64\text{--}68 \text{ km s}^{-1}$ in the maser vicinity (see below).

By inspecting the intensity maps in the entire velocity range, however, we only found two velocity intervals (around 67 km s^{-1} and 81 km s^{-1}) in which the ^{12}CO emission demonstrates more or less morphological correspondence with the SNR. As seen in Figure 3, at round 81 km s^{-1} , the CO emission exhibits a cavity structure, which is consistent with the SNR as delineated by the radio contours. The eastern bright radio shell of the SNR overlaps with most of the region of strong ^{12}CO emission, which covers the maser point. The radio emission fades from east to west, and a ^{12}CO arc composed of a few clumps is located along the faint radio boundary in the west. In the SNR boundary, four prominent *ROSAT* 0.1–2.4 keV X-ray patches are seen, two of which are located along the western radio shell and one of which is coincident with one of the western ^{12}CO clumps (“clump 1”, see Section 3.1.2).

At $V_{\text{LSR}} \sim 67 \text{ km s}^{-1}$ (Figure 3), a string-like ^{12}CO feature extends from the northeast to the south in the FOV, also covering the maser point, and most of it seems

to follow the western radio shell. However, two bright ends of the string are located outside the remnant, and little ^{12}CO emission corresponds to the radio brightness peak on the northern shell.

The integrated CO-line intensity ratio between the different transitions is used as kinematic evidence of interaction between SNR shocks and MCs (e.g., Seta et al. 1998; Jiang et al. 2010). Elevated ^{12}CO $J=2-1/J=1-0$ line ratios ~ 1 are also present on the boundary in the two velocity intervals of concern. At $76\text{--}79 \text{ km s}^{-1}$, the ^{12}CO $J=2-1/J=1-0$ ratios are apparently elevated to $\gtrsim 1$ (compared with $\sim 0.4\text{--}0.6$ in average) at several positions along the radio boundary. Apart from the north-western and southern boundaries, where an incomplete grid of points spaced every $2'$ was observed in PMOD for ^{12}CO ($J=1-0$) and thus the ratios there should be taken with caution, the ratio elevation in the northeast and the west is noteworthy. The northeastern ratio elevation (≈ 1) at around $(18^{\text{h}}51^{\text{m}}37^{\text{s}}, -00^{\circ}01'22'', \text{J2000})$ is located in a bright patch of radio emission, and the western elevation (≥ 0.9) around $(18^{\text{h}}50^{\text{m}}16^{\text{s}}, -00^{\circ}13'00'', \text{J2000})$ is coincident with a molecular clump (“clump 1”, see Section 3.1.2). In some interacting SNRs, the line ratios are observed to exceed unity (see Dubner et al. 2004), as found in SNR 3C396, however, due to some reasons such as beam dilution of the small filling factor of the ^{12}CO ($J=2-1$) emitting region compared to that for ^{12}CO ($J=1-0$), the observed relatively elevated ratios > 0.9 can also be a good probe of the SNR–MC interaction (Su et al. 2011). At $64\text{--}68 \text{ km s}^{-1}$, the line ratio is enhanced to > 1 in a region around $(18^{\text{h}}51^{\text{m}}55^{\text{s}}, -00^{\circ}10'00'', \text{J2000})$ adjacent to the OH maser point. By comparison, the line ratios are low in the two bright ends, which are outside the SNR boundary, of the eastern 67 km s^{-1} ^{12}CO string. The high line ratio near the maser point is another signature of disturbance of the molecular gas there by the SNR shocks and the gas emission at around 67 km s^{-1} is in the blue wings of the main-

TABLE 1
SOME PARAMETERS OF THE MOLECULAR GAS ASSOCIATED WITH
KES 78

Regions	$N(\text{H}_2)(10^{21} \text{ cm}^{-2})$		$M(M_\odot)$	
	X	LTE	X	LTE
Maser point	8.8	8.5		
Clump 1	4.3	3.0	$1.9 \times 10^3 d_5^2$	$1.3 \times 10^3 d_5^2$

NOTE. — Here two methods (indicated as “X” and “LTE”, respectively) are used to estimate the parameters of the molecular gas; see the last paragraph in Section 3.1.1.

body clouds at 81 km s^{-1} .

Figure 4 shows a large FOV of the ^{13}CO ($J=1-0$) environment at $80-84 \text{ km s}^{-1}$ around SNR Kes 78. The SNR is seen to be located in the side of some MCs. A long molecular strip in the northeast seems to connect the radio shell, although the LOS projection effect cannot be excluded, and the radio brightness peak along the northwestern SNR boundary is located at the connection point. The SNR also seems to be in contact with a molecular patch in the east and the OH maser is located at the interface. The eastern molecular patch seems to spatially correspond to some extent to the extended VHE γ -ray source HESS J1852-000 (considering the relatively large point-spread function of the H.E.S.S. observation).⁴ The ^{13}CO emission is much fainter in the west of the remnant than in the east. This, together with the faint radio emission in the west of the remnant, is consistent with a scenario that the remnant blows out to a low-density region. We also inspected the ^{13}CO ($J=1-0$) emission at around 67 km s^{-1} , but no distinct molecular structure was seen.

The above evidence from CO emission, such as the morphological correspondence of the CO emission with the SNR, the enhanced ^{12}CO $J=2-1/J=1-0$ ratio, and the ^{12}CO secondary peaks around 81 km s^{-1} as complicated broadened features, suggests that SNR Kes 78 is associated with the molecular gas at a systemic velocity of $\sim 81 \text{ km s}^{-1}$. There is a discrepancy of $\sim 5 \text{ km s}^{-1}$ between the LSR velocity of the OH maser and the systemic velocity of the associated MCs. A similar discrepancy is also seen in SNR W28, in which the velocity offset between the OH masers and the main-body MC is as high as 8 km s^{-1} (Claussen et al. 1997).

The column density of the molecular gas, $N(\text{H}_2)$, at the OH maser point (within the beam size $56''$ of the PMOD observation) is estimated with two methods and presented in Table 1. In the first method, $N(\text{H}_2)$ is calculated by using the ^{12}CO ($J=1-0$) velocity-integrated brightness temperature together with the mean CO-to- H_2 mass conversion factor $N(\text{H}_2)/W(^{12}\text{CO}) \approx 1.8 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ (Dame et al. 2001). In the second method, on the assumption of local thermodynamical equilibrium (LTE) with an excitation temperature

15 K and ^{12}CO ($J=1-0$) being optically thick, the ^{13}CO column density is converted to $N(\text{H}_2)$ using the relation $N(\text{H}_2) \approx 7 \times 10^5 N(^{13}\text{CO})$ (Frerking et al. 1982). The results obtained from the two methods are similar.

3.1.2. The Western Molecular Arc

A close-up tri-color image of the western molecular arc is presented in Figure 5(a). As previously mentioned, an X-ray patch is coincident with “clump 1” along the arc. The X-ray patch seems to extend northwards to another small clump (“clump 2”). (The two clumps are labeled in Figure 3.) A $24 \mu\text{m}$ mid-IR patch also seems coincident with “clump 1”. Another large, bright mid-IR patch in the north part of the image appears to cover the northernmost CO clump and, projectively, an ultracompact HII region at the velocity range of $7-26 \text{ km s}^{-1}$ (also see Section 4.4.2). Interestingly, some points with elevated ^{12}CO $J=2-1/J=1-0$ ratios (> 0.9) at $76-79 \text{ km s}^{-1}$ are seen at and around “clump 1” (see Figure 3, bottom right panel). Such ratios significantly higher than the average ($0.4-0.6$), as mentioned in Section 3.1.1, are also a signature of warm shocked molecular gas.

For the cores of two of the molecular clumps, two grids of CO spectra are presented in Figures 6 and 7, in which broad ^{12}CO line profiles at around 81 km s^{-1} can be found. For “clump 1”, blueshifted (left) broadenings of the ^{12}CO line profiles are seen at points “1a” (extending to at least 73 km s^{-1}), “1b”, “1e”, and “1h”. Bumps in the red wings of ^{12}CO lines are seen at “1b”, “1c”, and “1f” without corresponding ^{13}CO emission. The broad red wing of ^{12}CO ($J=1-0$) at “1e” is not decided because the ^{13}CO emission is not ignorable ($\gtrsim 3\sigma$) in the $86-90 \text{ km s}^{-1}$ interval. For “clump 2”, blueward broadening of the ^{12}CO line wings is seen at “2a”, “2c”, and “2f”, while a redward broadening is clearly seen at “2d”. These ^{12}CO line broadenings in red or/and blue side(s) are as large as about 10 km s^{-1} , which is strong evidence that the two clumps are shocked.

3.1.3. Other Molecular Components along the Line of Sight

We also find some noteworthy molecular structures at different LSR velocities in the Kes 78 field. Figure 8 shows the $V_{\text{LSR}} \sim 100 \text{ km s}^{-1}$ ^{13}CO ($J=1-0$) map compared with the *Spitzer* $24 \mu\text{m}$ mid-IR emission image. The CO emission at this LSR velocity (the velocity at the tangent point) is strong in the northeast region of the map (projectively across the northeastern border of the SNR) and, interestingly, is similar to the distribution of the bright $24 \mu\text{m}$ diffuse emission (also note a hollow, in the both wavelengths, outside the remnant). In both of the ^{13}CO and $24 \mu\text{m}$ emission maps, there is a north-south oriented branch stretching from the northeastern bright portion and well following the radio continuum “ridge” that is usually thought to be a structure of the remnant. At this LSR velocity, however, no molecular features other than the “branch” correspond to the other structures of the SNR (e.g., especially, the eastern radio shell). As will be discussed in Section 4.3, the faint radio ridge is likely to be irrelevant to the SNR.

Serendipitously, in the LSR velocity interval $86-97 \text{ km s}^{-1}$, we discern a bubble/ring-like ^{13}CO ($J=1-0$) structure of a radius $r_b \sim 15'$ (see Figure 9) centered at

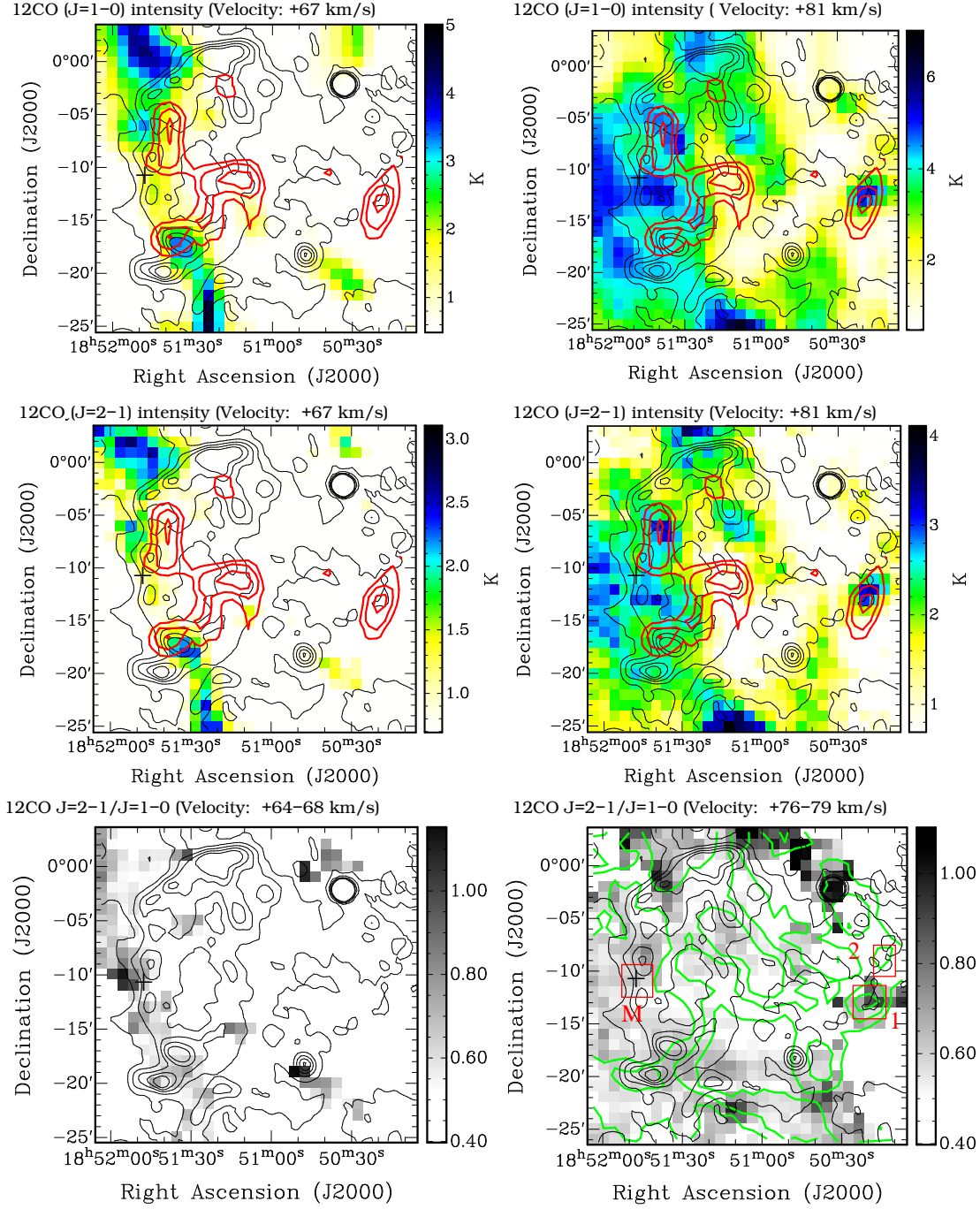


FIG. 3.— Upper and middle rows: intensity maps of ^{12}CO ($J=1-0$) and ^{12}CO ($J=2-1$) at the $V_{\text{LSR}} \sim 67 \text{ km s}^{-1}$ and $V_{\text{LSR}} \sim 81 \text{ km s}^{-1}$. Thick contours (red) represent the ROSAT 0.1–2 keV X-ray emission with levels of 0.22, 0.26, and 0.30 counts pixel $^{-1}$ (after being smoothed with a $3'$ Gaussian kernel). Bottom row: $^{12}\text{CO } J=2-1/J=1-0$ ratio maps in $64\text{--}68 \text{ km s}^{-1}$ and $76\text{--}79 \text{ km s}^{-1}$, after convolving the PMOD ^{12}CO ($J=1-0$) to the same beam size as the KOSMA ^{12}CO ($J=2-1$) data. The thick contours (green) represent the ^{12}CO ($J=2-1$) emission at $80\text{--}84 \text{ km s}^{-1}$ interval with levels 6.5, 10.1, and 13.7 K km s^{-1} . Here both $^{12}\text{CO}(J=2-1)$ and $^{12}\text{CO}(J=1-0)$ data used achieve a signal-to-noise ratio > 3 . Thin contours (black) of VGPS 1.4GHz continuum emission are overlaid in six panels with levels of 16, 20, 24, 28 and 32K. The plus sign in each panel denotes the OH maser point. The boxes, labeled with “M”, “1”, and “2”, define the OH maser region, the cores of “clump 1”, and “clump 2”, the spectra of which are shown in Figures 2, 6, and 7.

about ($18^{\text{h}}51^{\text{m}}30^{\text{s}}$, $-00^{\circ}09'00''$, J2000). Although it appears in almost the same direction as SNR Kes 78, with an angular size similar to that of the SNR, they are not completely coincident with one another and there is no corresponding feature between them. The systemic LSR velocity 91 km s^{-1} indicates that the bubble/ring is

located at the near distance $\sim 5.5 \text{ kpc}$ or the far distance $\sim 7.9 \text{ kpc}$, in the background of the SNR (see Section 3.2 for the method for deriving the kinematic distance). Using the second method for estimating the molecular column density described in Section 3.1.1), the mass of the bubble-like molecular gas is estimated to be

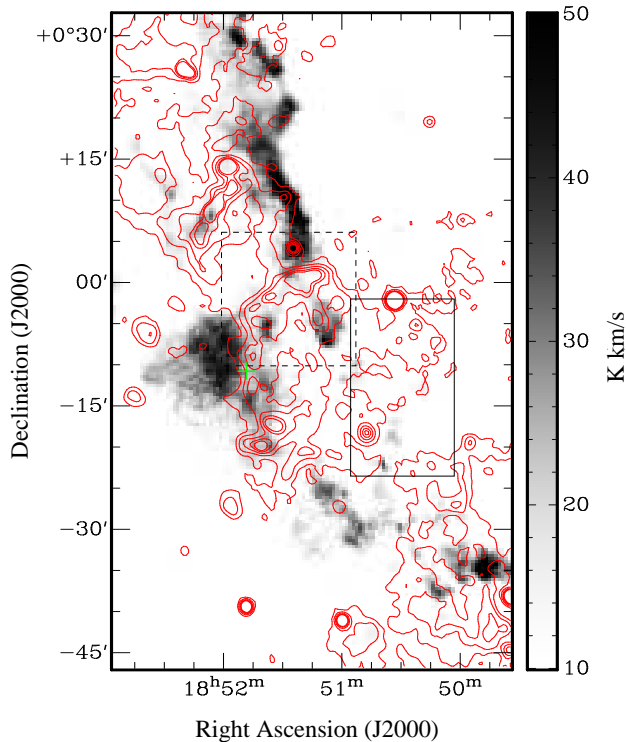


FIG. 4.— Molecular environment of Kes 78 in the 80–84 km s^{-1} interval (the BU-FCRAO GRS ^{13}CO ($J=1-0$) observation), overlaid with 1.4 GHz radio contours at levels 16, 19.75, 23.5, 27.25, and 31 K. The plus sign denotes the OH maser point. The two boxes indicate the spatial ranges of the two maps given in Figure 5.

$\sim 3.1 \times 10^5 M_{\odot}$ and $\sim 6.4 \times 10^5 M_{\odot}$ for the near and far distances, respectively. The nature of the structure will be discussed in Section 4.4.3.

3.2. The kinematic distance to SNR Kes 78

Due to the association of Kes 78 with the MCs at the systemic LSR velocity $\sim 81 \text{ km s}^{-1}$ (Section 3.1.1), there are two candidate kinematic distances to the SNR, 4.8 kpc (near side) and 8.6 kpc (far side). Here we have used the Clemens’ (1985) rotation curve of the Milky Way together with $R_0 = 8.0 \text{ kpc}$ (Reid 1993) and $V_0 = 220 \text{ km s}^{-1}$. The LSR velocity of the OH maser, 86 km s^{-1} , corresponds to similar distances 5.2 kpc and 8.3 kpc.

A modified HI absorption method (Tian et al. 2007) is next used to discriminate between the near and far distances. The HI spectra are extracted from two radio-bright regions as labeled in Figure 8 (regions “I” and “II”) and plotted as shown in Figure 10. A few distinct ($> 3\sigma$) absorption features appear below $V_{\text{LSR}} \sim 100 \text{ km s}^{-1}$, such as at 10 km s^{-1} and in the $80\text{--}90 \text{ km s}^{-1}$ interval. However, there is no absorption between 95 km s^{-1} and 110 km s^{-1} , which corresponds to the tangent point (at a distance around 6.7 kpc). Therefore, SNR Kes 78 is in front of the tangent point, namely at a distance smaller than 6.7 kpc; hence, the remnant is at the near distance 4.8 kpc. Hereafter we parameterize the distance as $d = 5d_5 \text{ kpc}$ (also considering the LSR velocity discrepancy of the OH maser from the systemic velocity).

3.3. XMM-Newton X-Rays from the Northeastern Boundary

3.3.1. X-Ray Image

From the available XMM-Newton EPIC-MOS X-ray data, we produce a tri-color X-ray image of the northeastern boundary of Kes 78 (as shown in Figure 5, panel (b); 0.5–1.0 keV coded in red, 1.0–2.0 keV in green, and 2.0–7.0 keV in blue), which is spatially correspondent to the radio brightest region. In the image production, the background subtraction and exposure correction have been applied, and adaptive smoothing has been made with a signal-to-noise ratio (S/N) ratio > 3 .

In the image, the X-ray-emitting region is well bordered by the radio contours, which indicate a sharp radio brightness drop at the blast shock. This part of X-ray emission was not detected in the ROSAT X-ray survey. The eastern portion of the shown region (dominated by the orange color) is apparently softer than the western portion (dominated by the green color), which is coincident with the radio brightness peak.

3.3.2. Spectral Analysis

Before the spectrum extraction, point-like X-ray sources in the FOV were detected with the wavelet method and removed from the events file. We then extracted the on-SNR X-ray spectra from two regions (labeled with “A” and “B”, as shown in Figure 11, the raw MOS image), which cover the hard (green) and soft (orange) portions (mentioned above), respectively. Because of the small amount of available counts, the MOS1 and MOS2 spectra were merged to increase the statistical quality. From the EPIC-PN observation, only the spectrum of “region A” was obtained. Thus for region A, both the MOS and PN spectra were used simultaneously, while for region B, only the MOS spectrum was used. As the X-ray source region is located near the edge of the FOV and is not very bright relative to the instrumental background, a double background subtraction method was used. The off-SNR source-free spectra were extracted from both the MOS and PN data (the extraction regions, as also shown in Figure 11, do not include the significant X-ray emission from the Galactic ridge in the center of the FOV). The respective instrumental background contributions from the same on- and off-SNR regions were obtained from the Filter Wheel Closed data of MOS and PN and were subtracted from the on- and off-SNR spectra. The individual on- and off-SNR spectra were adaptively binned to achieve a background-subtracted S/N of 3.

The XSPEC spectral fitting package (ver.11.3)⁶ was used. Each on-SNR spectrum was jointly fitted together with the off-SNR spectrum (Figure 12). The on-SNR diffuse background was determined by scaling the off-SNR emission according to the region sizes (Figure 12) and is phenomenologically well described by an absorbed *nei* + *blackbody* model. For the foreground absorption, the cross sections from Morrison & McCammon (1983)

⁶<http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/xanadu/xspec/xspec11/index.html>

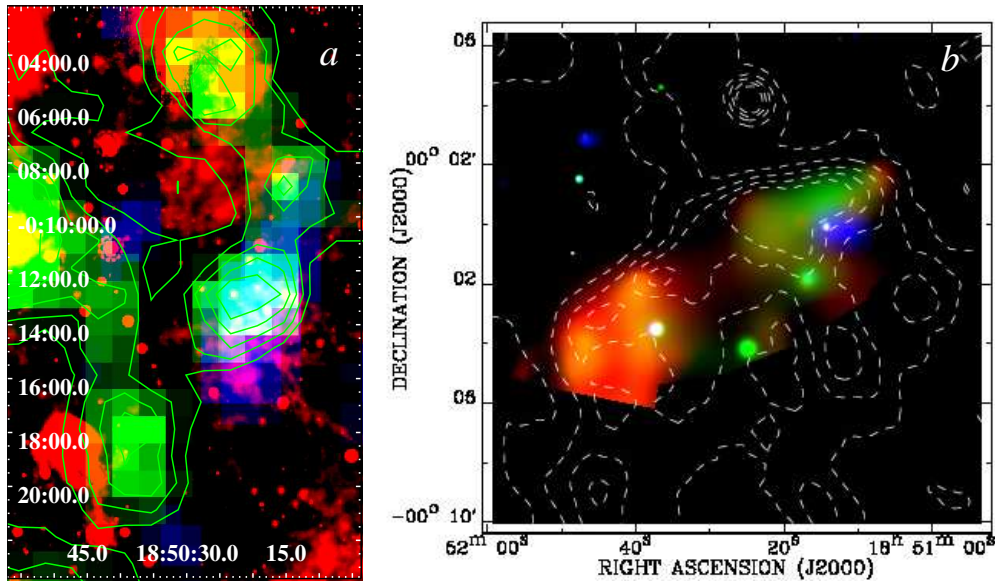


FIG. 5.— (a) A close-up tri-color image of the western molecular arc (the region of the image is indicated by the solid box in Figure 4). Red: *Spitzer* 24 μm emission; green: intensity map of ^{12}CO ($J=2-1$) integrated from 80 km s^{-1} to 84 km s^{-1} (overlaid with contours at levels of 6.5, 8.3, 10.1, 11.9, and 13.7 K km s^{-1}); and blue: *ROSAT* 0.1–2.0 keV X-ray map (smoothed to $3'$). (b) Tri-color XMM MOS X-ray image of the northeastern part of Kes 78 (the region of the image is indicated by the dashed box in Figure 4). The X-ray intensities in the 0.5–1.0, 1.0–2.0, and 2.0–8.0 keV bands are coded in red, green, and blue, respectively. The 1.4 GHz radio contours are at the same levels as those in Figure 3.

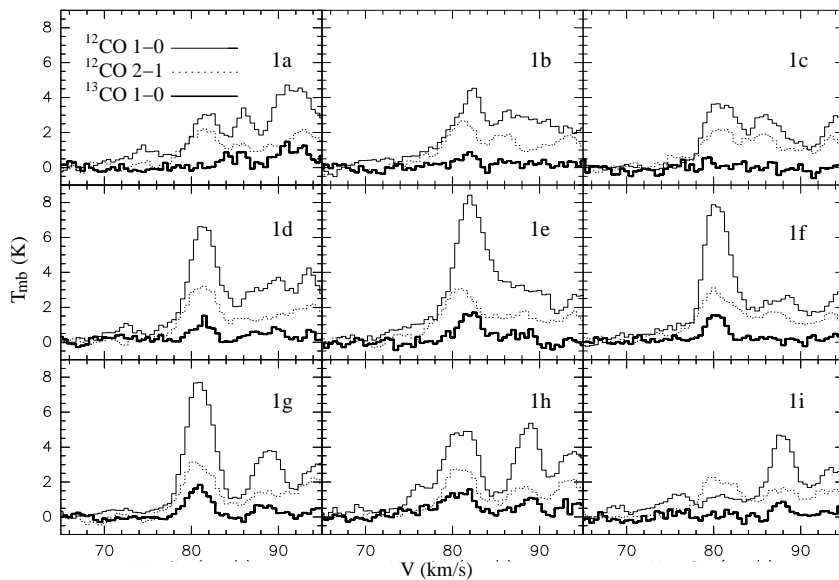


FIG. 6.— Grid of CO spectra restricted to the velocity range 65 km s^{-1} to 95 km s^{-1} in “clump 1” with $1'$ spacing (as labeled in the bottom right panel of Figure 3). All the spectra are not convolved to a uniform beam size.

were used, and solar abundances were assumed. The spectra of both regions A and B show distinct line features of $\text{Mg He}\alpha$ ($\sim 1.35 \text{ keV}$) and $\text{Si He}\alpha$ ($\sim 1.85 \text{ keV}$), indicating the thermal origin of the emission. The net SNR X-ray emission can be well fitted with an absorbed, non-equilibrium ionization thermal plasma model (*vnei*) with solar abundances. The fitting results are summarized in Table 2. The physical properties between the two regions are similar, except that the intervening hydrogen column density for region A is higher than that for region B. The relatively high N_{H} for region A is consistent with a contact of the SNR at the northeastern border (coincident with region A) with the dense molec-

ular strip (the shock strip interaction can naturally explain the radio brightness peak there; see Section 3.1.1 and Figure 4) and explains the fact that X-rays from region A are harder than those from region B (see Section 3.3.1). The gas temperatures are found to be 1.0–1.9 keV for region A and 0.7–2.9 keV for region B. The ionization timescales $n_e t_i$ of the X-ray-emitting gas of the two regions are both on the order of $10^{10} \text{ cm}^{-3} \text{ s}$, much smaller than $10^{12} \text{ cm}^{-3} \text{ s}$, which indicates that the hot gas has not yet reached ionization equilibrium. Estimates of the hydrogen number densities, n_{H} , derived from the volume emission measures ($f n_e n_{\text{H}} V$, where f is the filling factor of the hot gas and $n_e \sim 1.2 n_{\text{H}}$ is assumed) are also

TABLE 2
SPECTRAL FITTING RESULTS FOR THE NORTHERN SHELL OF KES 78 WITH
90% CONFIDENCE RANGES AND ESTIMATES OF THE GAS DENSITY

Regions	A	B
Net count rate (10^{-2} counts s^{-1})	3.61 ± 0.11 (MOS) 8.52 ± 0.27 (PN)	2.79 ± 0.10 (MOS)
χ^2_ν (dof)	1.04 (318)	1.17 (137)
N_H (10^{22} cm $^{-2}$)	$1.04^{+0.09}_{-0.08}$	$0.70^{+0.12}_{-0.09}$
kT_x (keV)	$1.51^{+0.34}_{-0.50}$	$1.30^{+1.57}_{-0.65}$
$n_e t_i$ (10^{10} cm $^{-3}$ s)	$1.82^{+0.89}_{-0.32}$	$2.03^{+4.88}_{-0.72}$
$f n_e n_H V / d_5^2$ (10^{56} cm $^{-3}$)	$1.12^{+0.31}_{-0.25}$	$0.58^{+0.69}_{-0.29}$
Flux(10^{-12} erg cm $^{-2}$ s $^{-1}$) ^a	$3.41^{+0.94}_{-0.77}$	$1.82^{+2.19}_{-0.92}$
$n_H / f^{-1/2} d_5^{-1/2}$ (cm $^{-3}$) ^b	$0.11^{+0.01}_{-0.01}$	$0.10^{+0.05}_{-0.02}$

NOTE. — The net count rates listed in the table are for the on-SNR spectra. The rates of the off-SNR spectra are $6.17 \pm 0.18 \times 10^{-2}$ counts s^{-1} and $1.26 \pm 0.04 \times 10^{-1}$ counts s^{-1} for MOS and PN, respectively.

^a The unabsorbed fluxes are in the 0.6–5.0 keV band.

^b In the estimate of the densities, we assume oblate spheroids for elliptical regions A (with half-axes $3.'36 \times 3.'36 \times 1.'84$) and B ($2.'74 \times 2.'74 \times 1.'75$).

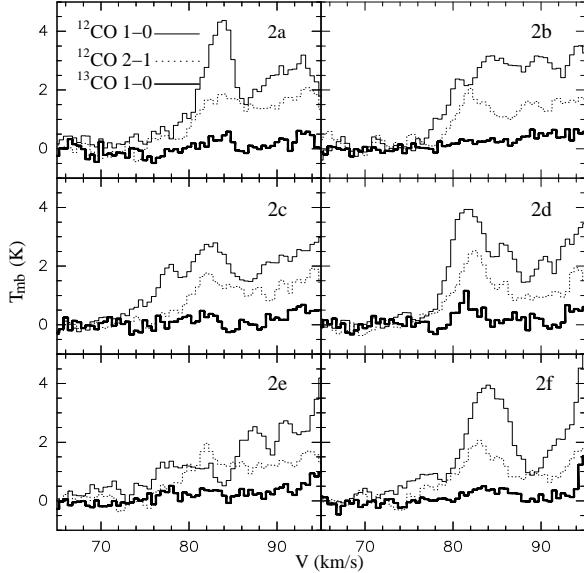


FIG. 7.— Grid of CO spectra restricted to the velocity range 65 km s^{-1} to 95 km s^{-1} in “clump 2” with $1'$ spacing (as labeled in the bottom right panel of Figure 3). All the spectra are not convolved to a uniform beam size.

given in Table 2. In the derivation of the densities we have assumed that the three-dimensional shapes of the elliptical regions (A and B) are oblate spheroids. Deviations from these assumptions and the non-uniformity of the X-ray-emitting plasma are consolidated into factor f of the individual regions.

4. DISCUSSION

4.1. Global Evolution of the SNR and the Progenitor

As revealed above (Section 3.1.1), SNR Kes 78 evolves in an interstellar environment of molecular gas with systemic velocity $\sim 81 \text{ km s}^{-1}$ and expands into a cloudy region in the east. Interestingly, the X-ray-emitting gas in the northeastern edge is characterized by a single thermal temperature (around 1.5 keV) and a low number density ($n_H \sim 0.1 f^{-1/2} d_5^{-1/2} \text{ cm}^{-3}$). This indicates that the blast wave in the northeast of the SNR propagates in the intercloud/interclump medium (ICM).

The velocity of the blast wave propagating in the ICM can be estimated as $v_s = [16kT_x/(3\bar{\mu}m_H)]^{1/2} \sim 1.1^{+0.1}_{-0.2} \times 10^3 \text{ km s}^{-1}$, where the fitted hot gas temperature for region A (for which the error bars of the spectrally fitted parameters are smaller than those for region B), $kT_x = 1.51^{+0.34}_{-0.50} \text{ keV}$, is adopted as the postshock gas temperature and the mean atomic weight $\bar{\mu}$ equals 0.61 for fully ionized plasma. We take the curvature radius of the eastern radio shell $\sim 12'$ as the SNR radius, namely, $r_s \sim 17d_5 \text{ pc}$, assuming that the dynamical age of the remnant, $t \sim 2r_s/(5v_s) \sim 6.1^{+1.0}_{-0.7} \text{ kyr}$, is derived with the Sedov (1959) evolution law. The explosion energy is $E = (25/4\xi)(1.4n_0m_H)r_s^3v_s^2 \sim 4.7 \times 10^{50} f^{-1/2} d_5^{5/2} \text{ erg}$, where $\xi = 2.026$ and $n_0 = n_H/4$ is the preshock intercloud hydrogen density. The ionization age of the X-ray emitting gas in the northeastern edge is inferred from the ionization timescales (see Table 2); for region A, $t_i \sim 4.4^{+2.2}_{-0.9} \text{ kyr}$ old, which is slightly, but reasonably, smaller than the dynamical age. Both estimates suggest a relatively young age of Kes 78.

The absence of [OIII] leads to an inference that the velocity of the shock wave responsible for the optical filamentary and diffuse structures is $< 100 \text{ km s}^{-1}$ (Boumis et al. 2009). This shock cannot be the SNR blast wave, otherwise the SNR should have been in the radiative phase with a considerably large age (Chevalier 1974): $0.31r_s/v_s \gtrsim 52 \text{ kyr}$, inconsistent with the X-ray properties obtained above. As Boumis et al. (2009) suggest, however, it is in the interstellar clouds that the slow shocks are propagating.

The bright radio emission in the east of the SNR is in agreement with the aggregation of the $\sim 81 \text{ km s}^{-1}$ molecular gas there and the inference that the clouds are clumpy. The radio continuum emission may arise from the blast shock that propagates in the ICM (Blandford & Cowie 1982). Contrarily, in the west, the $\sim 81 \text{ km s}^{-1}$ CO emission is weak and the radio continuum fades out.

As also mentioned in Section 3.1.1, in the west, the SNR expands into a relatively low-density region; but there the SNR seems to collide with a clumpy molecular arc. The entire SNR appears to be in a cavity surrounded by molecular matter. The molecular number density of

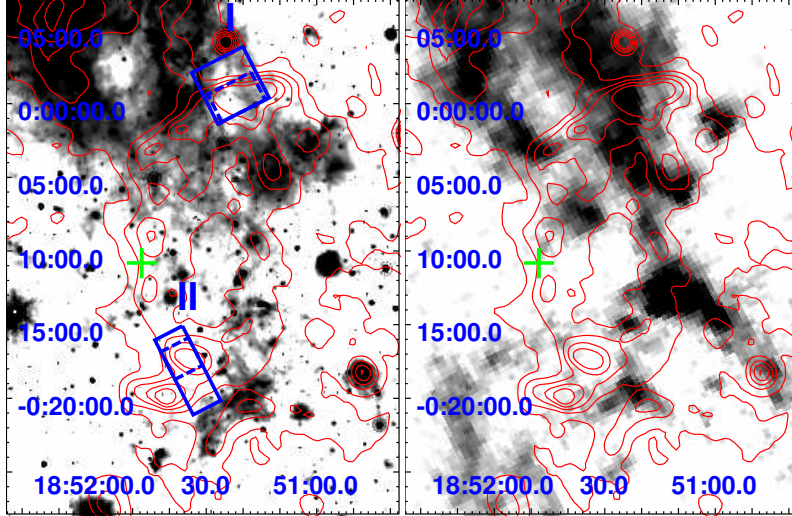


FIG. 8.— *Spitzer* 24 μm map (left panel) and BU-FCRAO GRS ^{13}CO ($J=1-0$) antenna temperature map integrated from 99 km s^{-1} to 101 km s^{-1} (right panel). Both of the maps are overlaid with 1.4 GHz radio emission contours with the same levels as those in Figure 3. The plus sign in each panel denotes the OH maser point. The two boxes labeled with “I” and “II” are regions from which the HI spectra (Figure 10) are extracted for discriminating two candidate distances (Section 3.2).

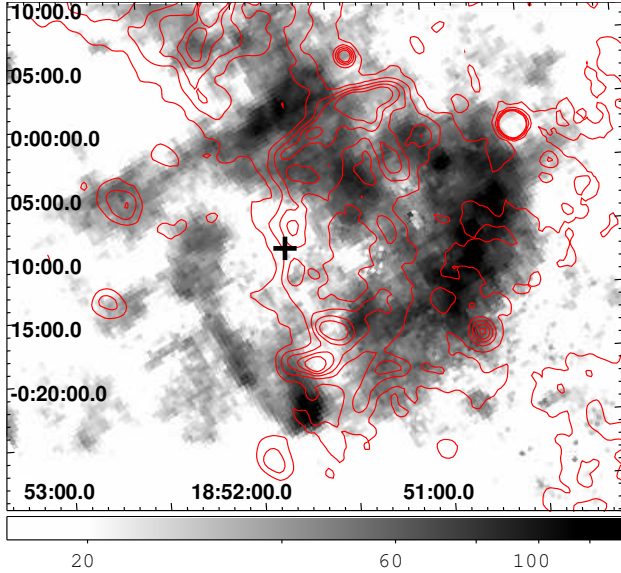


FIG. 9.— Image of the ^{13}CO ($J=1-0$) bubble-like structure at $86-97\text{ km s}^{-1}$ discerned from the BU-FCRAO GRS data, overlaid with 1.4 GHz radio emission contours with the same levels as those in Figure 4. The plus sign denotes the OH maser point.

“clump 1” along the arc is $\sim 270d_5^{-1}\text{ cm}^{-3}/188d_5^{-1}\text{ cm}^{-3}$, with an angular radius $2'$ adopted. The broad CO line wings and enhanced ^{12}CO $J=2-1/J=1-0$ ratios along the western arc imply a disturbance suffered by the molecular gas. Similar molecular arcs are seen in some other interacting SNRs, such as Kes 69 (Zhou et al. 2009) and Kes 75 (Su et al. 2009), in which the arcs are suggested to represent the debris of the clumpy shells of the progenitors’ wind bubbles. If the molecular cavity in Kes 78 was created by the progenitor, using the linear relation between the main-sequence wind bubble size and the progenitor’s mass (Y. Chen, et al., 2011, in preparation ⁷), $R_b = 1.21M/M_\odot - 8.98\text{ pc}$, the cavity radius

⁷<http://astronomy.nju.edu.cn/~ygchen/papers/Rb-M/Rb-M.pdf>

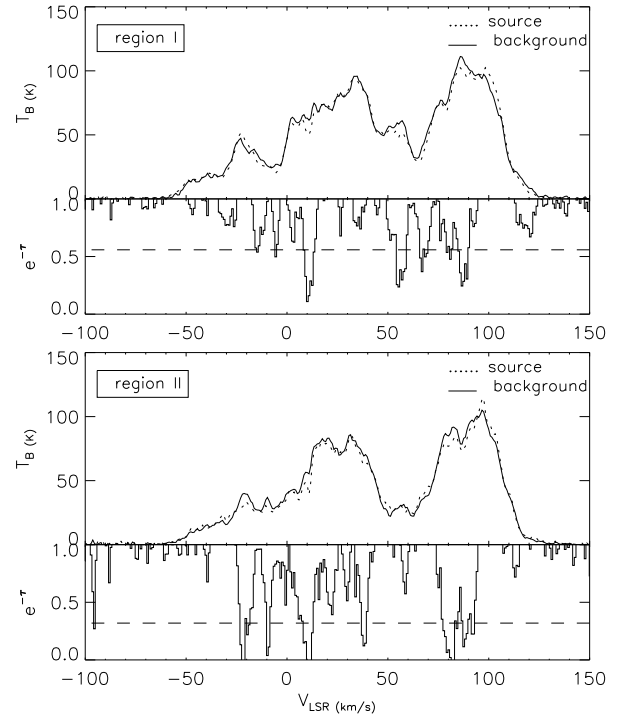


FIG. 10.— VGPS HI spectra extracted from the regions “I” and “II.” The long-dashed lines represent the 3σ level.

17pc would imply a mass around $22M_\odot$ for the progenitor star of SNR Kes 78, which seems to be of O9 type.

4.2. Pressures in the multi-phase gases

We have arrived at such a scenario in Section 4.1 that SNR Kes 78 evolves in a cloudy interstellar medium, the blast wave in the ICM giving rise to the X-rays and the cloud shocks in the dense clouds to the optical emission. The thermal pressure of the X-ray-emitting gas is $2.3n_{\text{H}}T_x \sim 6.0 \times 10^6 f^{-1/2} d_5^{-1/2}\text{ cm}^{-3}\text{K}$ and \sim

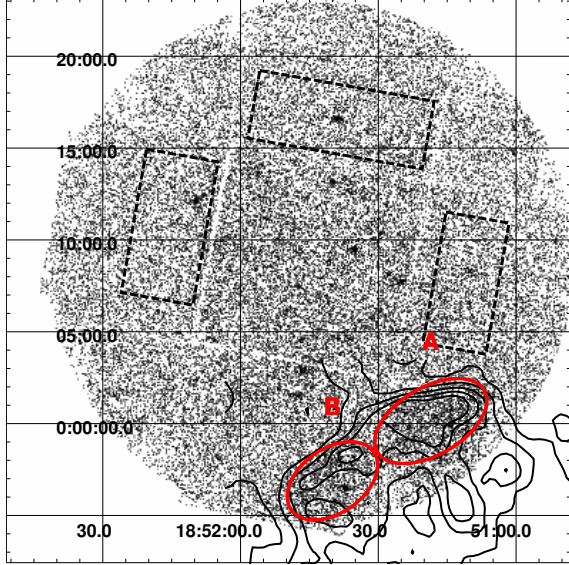


FIG. 11.— XMM-Newton raw image of Kes 78. Two solid ellipses (labeled “A” and “B”) and three dotted boxes are defined, respectively, for source and background spectrum extraction. The contours of 1.4GHz radio emission outline the northeastern area of Kes 78, which have the same levels as those in Figure 4.

$4.0 \times 10^6 f^{-1/2} d_5^{-1/2} \text{ cm}^{-3} \text{ K}$ for regions A and B, respectively. According to the density-sensitive line ratio of [SII] $\lambda\lambda 6716/6731$, B09 determined the electron densities in the shocked clouds to lie below 200 cm^{-3} and suggest a temperature of the electrons $\sim 10^4 \text{ K}$. The upper limit of the thermal pressure in the optically emitting structures is estimated to be $\sim 4 \times 10^6 \text{ cm}^{-3} \text{ K}$, which is similar to the pressure derived for the X-ray-emitting gas. Thus, it seems that the shocked ICM may be in pressure balance with the shocked clouds.

However, there is significant pressure variation in the multi-phase cloudy gases in the east of the remnant. The 1720 MHz OH masers are believed to arise from very dense ($\sim 10^5 \text{ cm}^{-3}$) regions of MCs that are shocked by the C-type shock waves (Lockett et al. 1999). By means of Zeeman splitting, the LOS component of the magnetic field in the Kes 78 OH maser region, B_{los} , was measured to be $1.5 \pm 0.3 \text{ mG}$ (Koralesky et al. 1998). For a randomly oriented field, the post shock field strength $B_{\text{ps}} = 2B_{\text{los}}$ (Frail & Mitchell 1998; Crutcher 1999). Thus, the magnetic pressure in the OH maser region of Kes 78 is $B_{\text{ps}}^2/(8\pi k) \approx 2.6 \times 10^9 \text{ cm}^{-3} \text{ K}$, which is over two orders of magnitudes higher than the thermal pressures of the X-ray emitting intercloud plasma and the optically emitting filamentary and diffuse structures. Notably, similar pressure variation from the X-ray emitting gas to the OH maser regions is seen in SNR W28 (Rho & Borkowski 2002). Such a pressure contrast has been suggested to be caused by the interaction of the radiative shell with the dense molecular clumps (Chevalier 1999).

4.3. The Dubious Ridge

The radio “ridge” was sometimes suspected to be the western part of an elongated SNR shell (e.g., Caswell et al. 1975). We have seen in Section 3.1.3 that the radio ridge appears to be coincident with the north-south oriented $24 \mu\text{m}$ IR branch, which extends from the bright emission in the northeastern region outside the remnant’s

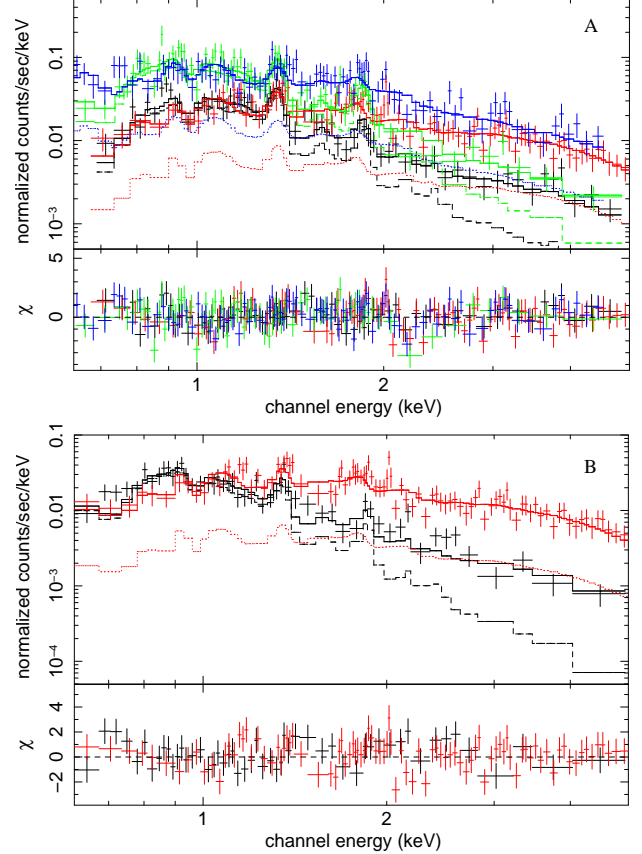


FIG. 12.— XMM-Newton EPIC spectra of regions A and B defined in Figure 11. The on-SNR spectra (black solid lines for EPIC-MOS and green solid line for EPIC-PN) are fitted as a sum of the diffuse background emission and the net SNR emission. The on-SNR diffuse backgrounds (red dotted lines for MOS and blue dotted line for PN) are scaled from the off-SNR spectra (red solid lines for MOS and blue solid line for PN), which are mimicked by an absorbed *nei* + *blackbody* model. The net SNR spectra (black dashed lines for MOS and green dashed line for PN) are fitted well with an absorbed *nei* model.

radio boundary, the $24 \mu\text{m}$ emission in and around the eastern region of the SNR has a strikingly similar distribution to the $V_{\text{LSR}} \sim 100 \text{ km s}^{-1}$ ^{13}CO emission. This leads us to suspect that the radio ridge is not a part of the SNR that is associated with the $\sim 81 \text{ km s}^{-1}$ MCs, but rather is associated with the $\sim 100 \text{ km s}^{-1}$ MCs, which is essentially located at the tangent point of the inner Scutum-Centaurus spiral arm of the Galaxy. On the other hand, optical observation towards Kes 78 finds no significant [SII] from the radio ridge, while in the eastern, northern, and southern regions of Kes 78, the [SII] emission is evident, with the [SII]/H α ratio > 1.3 (Boumis et al. 2009). As the [SII] strength in the shock-ionized gas is comparable to the H α strength and is much fainter in the photoionized gas (HII regions or planetary nebula; Dennefeld & Kunth 1981), the radio emission is probably of thermal origin and possibly arises from star formation region(s). Further study estimating the radio spectral index for the radio “ridge” will test its nature.

4.4. Other Sources in the Kes 78 Field

4.4.1. PSR1850-0006

Since the progenitor of Kes 78 was probably a massive star (see Section 4.1), a neutron star or pulsar may have

been left after its explosion. PSR1850-0006 is projected in the northwestern portion of the SNR (Keith et al. 2009). However, with a rotational period of 2.2 s and a period derivative of $4.3 \times 10^{-15} \text{ s s}^{-1}$, the pulsar has a characteristic age of about 8 Myr, which is much older than the age of SNR Kes 78 (Section 4.1), disfavoring an association between PSR1850-0006 and the SNR.

4.4.2. HII Regions

The ultracompact HII region located at ($18^{\text{h}}51^{\text{m}}25^{\text{s}}$, $00^{\circ}04'07''$, J2000) is northeast of the SNR, as seen in Figure 4. It is coincident with the massive star formation region IRAS 18488+0000 (Bronfman et al. 1996) and may be associated with SNR Kes 78. In fact, a 22 GHz H_2O maser at $V_{\text{LSR}} \sim 80 \text{ km s}^{-1}$, which is very similar to the systemic LSR velocity of the MCs with which the SNR is in contact, is suggested to be associated with the star formation region and is at the same distance (5 kpc) as we determine here for the SNR (Beuther et al. 2002). The HII region or IRAS 18488+0000 is located at the northern molecular strip with which the SNR interacts and only $2'$ north of the radio brightness peak of the SNR.

Another ultracompact HII region at ($18^{\text{h}}50^{\text{m}}31^{\text{s}}$, $-00^{\circ}01'55''$, J2000) (Garay et al. 1993) appears to be projectionally located on the northwestern boundary of the SNR and connects the western molecular arc in the northwest, as seen in Figure 4. In this HII region, six 22 GHz H_2O masers were detected at the LSR velocity range $\sim 7\text{--}26 \text{ km s}^{-1}$ (Hofner & Churchwell 1996). There may not be associated with the SNR because they are at different LSR velocities.

4.4.3. The Molecular Structure at $V_{\text{LSR}} \sim 91 \text{ km s}^{-1}$

As concluded in Section 3.1.3, the bubble/ring-like structure discovered at $V_{\text{LSR}} = 86\text{--}97 \text{ km s}^{-1}$ is at a further distance (5.5/7.9 kpc) than that to SNR Kes 78 (4.8 kpc). If it is an interstellar bubble, then the mean molecular number density of the undisturbed gas before the bubble was created is $\sim 77/54 \text{ cm}^{-3}$ for the near/far distance. Adopting an expansion velocity $v_b \sim 7 \text{ km s}^{-1}$ (FWHM of the ^{13}CO line at $\sim 91 \text{ km s}^{-1}$), the kinematic energy is $\sim 1.5/3.1 \times 10^{50} \text{ erg}$. If the bubble is blown by a wind, it has an age $3r_b/(5v_b) \sim 2.0/2.9 \times 10^6 \text{ yr}$ and the mechanical luminosity of the wind is $\sim 1.2/1.8 \times 10^{37} \text{ erg s}^{-1}$ according to the canonical evolutionary law of a wind bubble given by Weaver et al. (1977). This ring/bubble-like structure may not be a distinct SNR. Actually, for an SNR in the radiative stage (Chevalier 1974), its age is $0.31r_b/v_b \sim 1.0/1.5 \times 10^6 \text{ yr}$, but the supernova explosion energy would be $4.6/9.6 \times 10^{51} \text{ erg}$, which is much higher than the fiducial value $1 \times 10^{51} \text{ erg}$.

5. SUMMARY

We have investigated the molecular environment of the Galactic SNR Kes 78 using the CO observations in PMOD, KOSMA, and FCRAO and have performed an XMM-Newton X-ray spectroscopic study for the northeastern edge of the remnant. The main results and conclusions are summarized as follows:

1. SNR Kes 78 is found to be associated with the MCs at a systemic LSR velocity of 81 km s^{-1} . At around this velocity, the SNR is revealed by the ^{13}CO observation to be in the side of some dense MCs and is consistent in extent with a cavity of ^{12}CO gas. The SNR expands into a cloudy dense region in the east, where the OH maser emission arises and the bright radio shell overlaps with most of the region of strong ^{12}CO emission. Broadened ^{12}CO line profiles discerned in the eastern maser region and the western clumpy molecular arc, the elevated ^{12}CO $J=2-1/J=1-0$ ratios along the SNR boundary may be signatures of shock perturbation in the molecular gas.
2. The association of SNR Kes 78 with the $\sim 81 \text{ km s}^{-1}$ MC, together with the HI absorption along the LOS, places the SNR at a kinematic distance of 4.8 kpc.
3. The X-rays arising from the northeastern radio shell are emitted by underionized hot ($\sim 1.5 \text{ keV}$), low-density ($\sim 0.1 \text{ cm}^{-3}$) plasma with solar abundance, and the plasma may be of intercloud origin. Especially, the X-rays from the radio brightness peak, where a long molecular strip appears to connect, suffers a heavier absorption than those from other parts along this XMM-observed section of the shell. The thermal pressures of the X-ray-emitting gas and the optically emitting structures along the shell are lower than the magnetic pressure in the OH maser region by up to two orders of magnitudes. The age of the remnant is inferred to be about 6 kyr.
4. The size of the molecular cavity in Kes 78, which is assumed to be created by the main-sequence wind, implies the progenitor's mass to be around $22M_{\odot}$.
5. The north-south oriented radio continuum ridge west of the bright shell is suggested to be irrelevant with the SNR, but related to a $\sim 100 \text{ km s}^{-1}$ CO branch at the tangent point, which corresponds to IR bright, low-[SII]/H α ratio star formation region(s).
6. Along the LOS toward SNR Kes 78, we discern an irrelevant bubble/ring-like ^{13}CO structure $15'$ in angular radius at the LSR velocity 91 km s^{-1} , but the possibility of it being a separated SNR is ruled out.

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